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ADVANCEMENTS IN NEUTRON RADIOGRAPHY WITHIN THE DEPARTMENT OF THE ARMY

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14. ABSTRACT

The radiographic laboratory within the U.S. Army's Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, is a known leader in the creation of new or advanced nondestructive testing (NDT) technologies and inspections. Within the past five years, neutron radiography (NR) has been a main focus of development where previous commercial off the shelf systems were inadequate to use. An increase in inspection technology was desired due to the rising need to have new measures to detect defective conditions to have assurance that a product works as intended and to ensure safety and reliability. The NR inspection shows the next evolution in nondestructive examination that many areas within the Department of Defense (DoD) require. The NR has the ability to image through and behind materials and configurations that are otherwise physically impossible to inspect with any other NDT method. This report presents the latest developments in neutron generator technology including advances in shortening exposure times, increasing image quality, and showing other viable attributes that exceed previous capabilities when using electronic neutron sources. The potential and subsequent uses applicable within the DoD require these new developments to make the inspection method practical. This includes the need for low-rate production quality control, reverse engineering, and testing throughout the development of newly designed defense systems. Specific examples of munitions and weapon system inspections will be shown as well as the progress and overall capability of this new technology. A brief review on the next stage in testing and planned phases to expand the NR inspection method will also be included.

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PREFACE

This report is the third installment of the neutron radiographic inspection program under development within the U.S. Army's Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ. The program has established viable baseline data on what advancements are necessary to expand the inspection into low-rate production use within the Department of Defense. Recent technology developments have brought the neutron radiographic capability even closer to realization without the need for a reactor or research accelerator. The inspection of munitions and weapon systems for safety, quality, and intended function are the main focus of the project.

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INTRODUCTION

The current neutron radiography (NR) program at the U.S. Army Armament Research, Development and Engineering Center (ARDEC), Picatinny Arsenal, NJ, began by base-lining previous commercial off-the-shelf neutron generators and the radiographic imaging capabilities that could be achieved with them. The baseline showed major areas of deficiencies in neutron generator technology and how far behind the inspection process was without the use of a reactor, isotope, or research accelerator.

Previous work at ARDEC included the use of isotopes, specifically Califorinum-252 (Cf-252), to perform NR. This work was presented several decades ago and showed valuable achievements in its application. The program was never fully realized due to several inherent disadvantages of working with radioactive isotopes. The regulatory controls, the increasing costs to maintain these sources, and the issue of half-life losses were the primary reasons for the deterioration of the program.

The most recent developments in neutron generator technology have led to more advanced experiments, testing, and imaging. Two different types of electronic deuterium only fusion generators have made significant leaps in the ability to acquire shorter exposure times and increased image quality over their predecessors. This report covers the initial imaging experiments for these two new systems. Potential steps to broaden their use across the Joint Services, specifically for the inspection of munitions and weapon systems, will also be discussed.

NEUTRON RADIOGRAPHY NEEDS SPECIFIC TO THE DEPARTMENT OF DEFENSE (DoD)

Previous Nondestructive Testing (NDT) Inspection Constraints

Within the DoD, specifically within the Joint Services (U.S. Army, U.S. Navy, U.S. Air Force, and U.S. Marines), function, safety, and quality control are the areas where the highest priority is given. For a large portion of munitions and weapons systems, numerous NDT inspection methods are used. Methods commonly used in the industry are: ultrasonic testing (UT), electromagnetic testing, magnetic particle testing, radiographic testing (RT), penetrant testing, visual testing, acoustic emission, NR, and other specialized methods such as infrared or thermography. These inspection processes are used to confirm, verify, and assure these top priorities remain at consistent levels while also allowing for seamless throughput during production. In general, each NDT method has its own materials, properties, and conditions in which they are applicable.

For instance, UT is valuable for detecting sub-surface conditions in homogeneous materials. The UT is capable of inspecting metallic slabs and billets, piping and tubing, and shell bodies used for munitions. Conditions such as voids, cracks, inclusions, and delaminations (separations) can be detected to determine the integrity of the materials or parts prior to further assembly or fielded use. Under different circumstances, the UT may become impractical, inaccurate, or overall useless; in which case, another NDT method may be needed. For example, if an individual has a part that has extremely rough surfaces, is constructed with very porous materials, and is constructed of vastly different layered materials, the UT may not be useful. Under general circumstances, the UT requires very close contact with the part surface to get accurate measurements, may result in excessive false readings due to the porous material, and may not achieve a high enough return signal or desired resolution to determine if defective conditions are present in the different layers. The major concern here is that each method has its designated purpose, and in certain designs and configurations, no viable inspection method may be available. Certain characteristics that determine the function or safety of a part or system may not be detectable with current technology. In other situations, the

inspection may not be practical if costs to implement it are in excess of its added value to the overall production process.

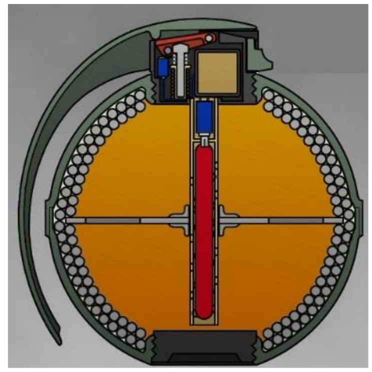
Within ARDEC, new materials, products, sub-components, and redesigns of older legacy systems are under continuous change. The need to update, upgrade, and focus on increasing function without creating more burden to the user is putting increased demand in new inspection technologies, methods, and techniques. For munitions, UT and RT are the most widely used inspections. The RT can verify that energetics are present in full up assemblies and can determine if certain conditions will cause unwanted malfunction prior to use such as cracks in the explosives and damaged or armed fuzes. However, with the capability that RT brings, using x-rays or gamma-rays, certain composites, and high density materials make the inspection useless. In items where lead, tungsten, copper, or steel are used, x-rays tend to have reduced reliability in detecting materials inside assemblies made of such elements. This is due to the high physical density they all have in which x-rays cannot adequately penetrate through them. In some cases, higher energy (>1MeV) can be used to image through such materials depending on the thickness. However, in most cases, RT inspections within the defense sector involve low density and/or thin components placed inside high density casings or materials. In either situation, using high energy x-rays may cause the internal parts to be lower in contrast, have low resolution, or be completely undetectable. This is where NR becomes applicable. In general, by using neutrons instead of x-ray photons, high density materials become easy to image through, and low density materials become the focus of the inspection. Note that this is not an absolute statement since neutron radiation is based on nuclear cross section rather than density, but for the discussion at hand, it is applicable.

Product Design Applications

Fragmenting Liners and Ball Bearings

Direct examples that begin to show the ability of neutron imaging are provided in figure 1, and a few additional examples can be found in reference 1. Products designed and constructed of complex shapes and vastly different material densities and thicknesses generally impede the use of imaging with x-rays. Various munitions and weapon systems such as hand grenades, mines, medium caliber cartridges, mortars, and large caliber rounds have or are being designed to be anti-personnel devices. Such designs use fragmenting liners or ball bearings of different shapes, sizes, and patterns that project them out from the device when functioned. This allows a large volume to be covered by a vast number of smaller fragments to remove personnel while minimizing collateral damage. Details that go into these devices are exceedingly complicated and reduce the ability to use x-ray imaging for inspection.

(a)
Internal cutaway
of a shotgun shell

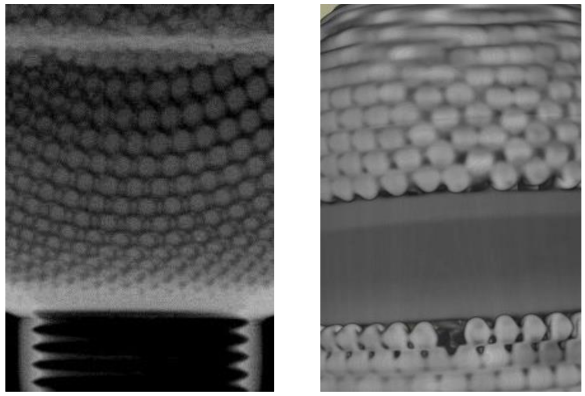


(b)
A representation of a ball
bearing lined hand grenade

Figure 1
Fragmenting devices

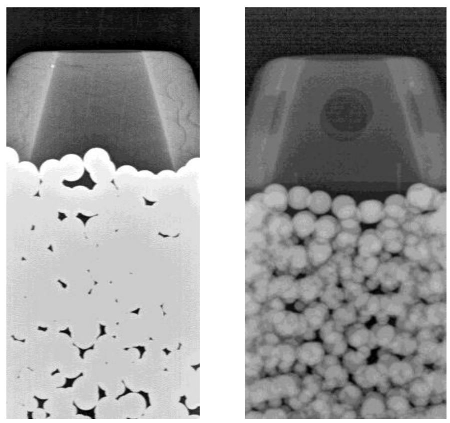
In many cases, even performing three-dimensional reconstructions and volume renderings using computed tomography (CT) are ineffective when using x-rays. Several additional constraints arise using CT. Each plane that is imaged contains blocked information behind each high density ball bearing or etched line. This creates an area behind the ball that has the wrong information as well as an area surrounding the high density region that is over embellished on the dimensions of the ball itself. This effectively skews or removes information that is internal to the rest of the part under inspection. Certain digital processes can be performed to reduce these effects, specifically beam hardening algorithms. However, the digital processing cannot completely eliminate it or be used in all situations. In some cases, CT can still provide information to determine if the integrity of the part conforms to its design specifications, but in other situations, NR may be required.

Figures 2 and 3 show general samples where using x-rays to image has reduced reliability and where NR may have applications. As can be seen in figure 2a, radiograph (x-ray) of a grenade shows the etched fragmenting liner, which reduces the reliability to verify if explosive material is present inside the casing. Figure 2b shows a volume rendering of a medium caliber fragmenting projectile. Blurred regions are seen that affect the ability to assess internal components. Figure 3a is an image taken using 350keV photons in order to acquire information about the epoxy holding the bearings together. Figure 3b is a 2MeV image to show increased penetration through the bearings but a reduction in the contrast of the epoxy. The state of the main portion of the epoxy around the bearings cannot be determined in either image.



(a) (b)

Figure 2
Radiograph and volume rendering images



(a) (b)

Figure 3
Two radiographs (x-ray) showing an optimized technique of a ball bearing assemblies

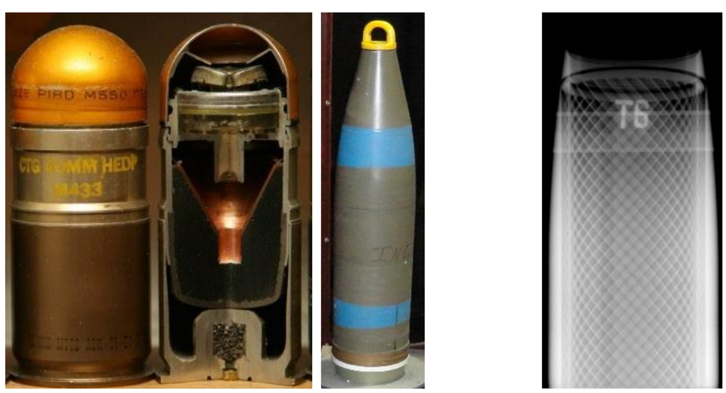
Dense Casings with Layered Explosives

Numerous other applications require NR inspection, but the second focus in this report includes the use of layered explosives inside heavy, high density casings such as steel. Throughout the production of munitions and weapons systems, multiple assembly stages may occur. For certain systems, multiple NDT inspections may occur for each sub-component. Those sub-components may be assembled into larger pieces of the entire system, in which those may also be combined to create the finished product. Radiography is generally used to perform inspections at certain assembly stages and during the final construction. This ensures everything was put together correctly and assists in the quality control for each stage in the process. However, in various designs once all the sub-assemblies are combined, so many different materials, thickness changes, density variations, and complex shapes can combine to obstruct most NDT inspections, even RT.

In the majority of instances, the inner most pieces reflected the most significant changes when compared to those of the entire assembly. These pieces are much smaller in size, may have lower density, and require the most stringent inspection criteria. All of these requirements together can prove to be difficult if the right combinations are assembled. An example of a configuration that

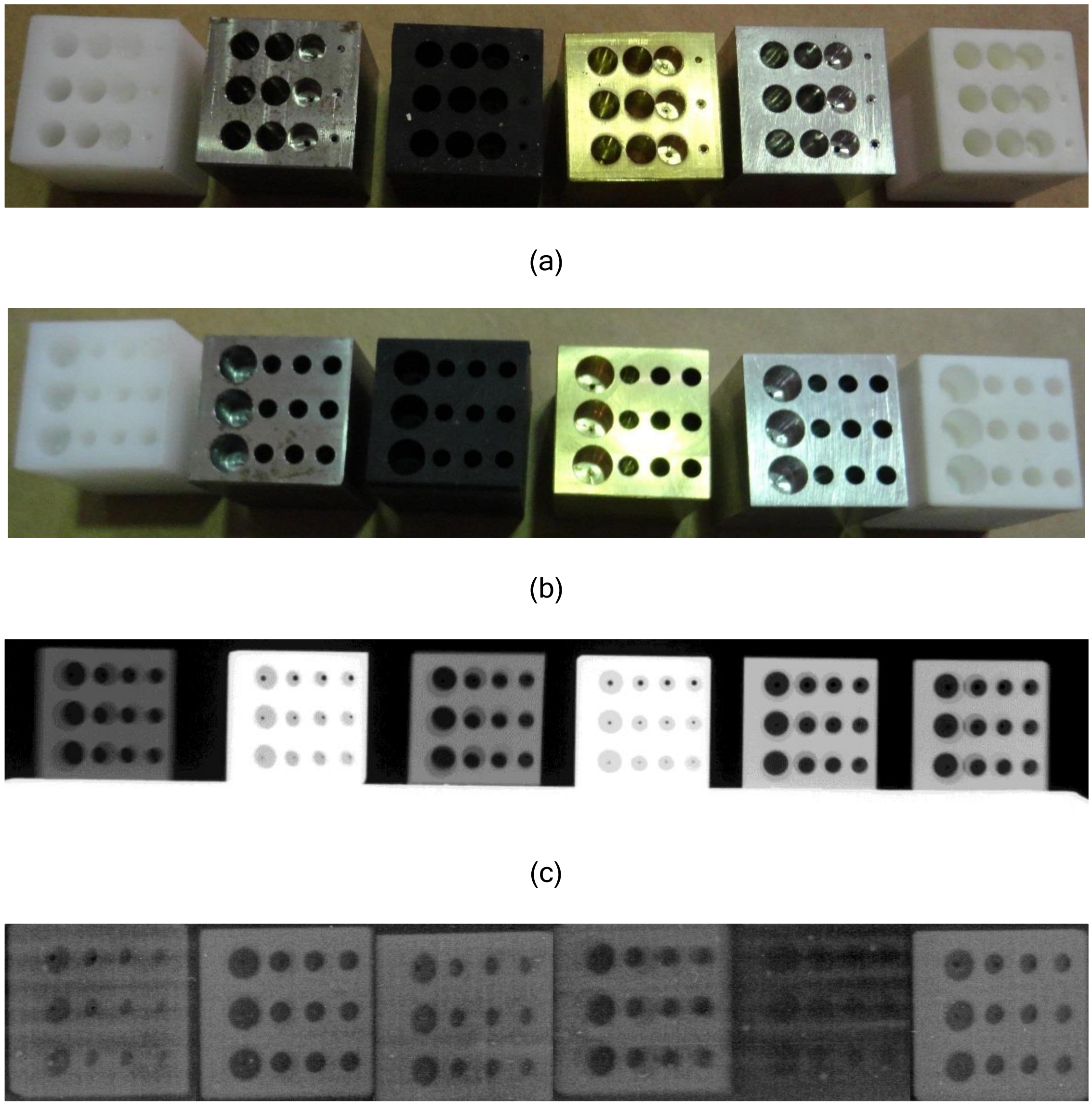
is a physically limiting design is a part that is constructed of a steel exterior, contains a layer of clay, has a region of tapped threads at its center, and has a low density magnesium insert placed within the interior of the threads. In this situation, the assumption is made that the most critical component to ensure functioning was the presence of the magnesium insert. The detection reliability would be greatly reduced in the situation where the thickness of the magnesium insert was very small, was not a significant portion of the entire linear attenuation of the assembly, or the region of the threads overlays the magnesium insert. The latter case would cause an increase in internal scattered radiation and sharp changes in thickness directly over the area of interest. Given specific thicknesses, densities, and the photon energy used for each component, the linear attenuation formula from the annual book of American Society for Testing and Materials (ASTM) Standards could be used (ref. 2). Performing this calculation would provide the nominal value for the expected percent change in equivalent thickness that is detectable. It also would provide a qualitative value of the image sensitivity and be a component of the overall image quality. This value is generally verified using image quality indications (IQI), representative quality indications, or other such standards as specified in ASTM E 1742 and its applicable references (ref. 2).

In certain cases, such as the one portrayed, the design may not allow for the detection of the inner most material nor verify that it does not contain cracks, cavities, or other defective conditions. In such situations, NR inspections can be more advantageous or useful over x-rays or gamma-rays. In assemblies that use high density or thick materials such as steel, brass, titanium, wide sections of aluminum, etc., neutrons will generally pass through such areas unabated in comparison to x-ray photons. In addition, neutrons are less likely to be affected by sharp thickness changes in those materials. Detection through areas such as tap and die components, like threaded regions and screws, can be increased. Effective examples of this type of design are shown in figure 4 along with the reduced or unreliable detection of surrounding materials. Figure 4a shows a 40-mm high explosive, dual purpose cartridge M433, and figure 4b shows a large caliber projectile with various internal lines. Figure 5 also shows a valid comparison between the attenuation differences in common materials when using x-rays versus neutron radiation. The materials include: polyethylene, steel, rubber, brass, aluminum, and ceramic (from left to right). Figures 5a and 5b show visual images of both sides of the cubes, figure 5c shows an x-ray image, and figure 5d shows the neutron image. These IQI cubes were designed and built at ARDEC.



(a) (b)

Figure 4
Examples of layered materials depicting situations where reduced effectiveness using x-rays arises



(a)

(b)

(c)

(d)

Figure 5
Comparative radiographs showing the different attenuations of common materials

ADVANCED NEUTRON GENERATORS

Evolution of Neutron Radiography

In 2013, the ARDEC radiographic laboratory took delivery of two new state of the art neutron generators. These generators were developed through the Small Business Innovation Research program. The systems were derived using the same physical process of creating neutrons using the fusion reaction between deuterium atoms/ions but were designed and built independently from one another. The first of these two generators was developed by Phoenix Nuclear Laboratories (PNL), LLC (contract no. W15QKN-08-C-0515), Morona, Wisconsin, while the second was completed by Starfire Industries, LLC (contract no. W15QKN-08-C-0516), Champaign, IL, (refs. 1 and 3). Both of these systems made significant strides in creating higher neutron yields. These systems also

maintained a small size, were able to be operated easily by a single individual, had increased generator lifetimes, and ensured consistent reliability during continuous use. Previous neutron generators were limited to yields less than 5E8 n/s at 130 kV using a maximum of 9 watts of power. These older generators mainly used solid targets that were susceptible to short life spans between 1,000 and 1,500 hr of continuous use due to degradation caused by heat loading. Although past generator designs were very small in size, the reliability of them was suspect. Excessively occurring electrical faults have been an issue in earlier baseline experiments with these types of generators, which are outlined in references 4 and 5.

Overview of the Phoenix Nuclear Laboratories Neutron Generator

The PNL neutron generator consists of an ion source that creates a deuterium plasma that becomes positively ionized. These ions are then extracted and accelerated into an electrically grounded target containing deuterium in a gaseous form. When the positive ions collide into the gas, fusion events between the deuterium take place, creating neutrons and tritons. Both events have a 50% probability of occurring. The remaining energy left from the reaction becomes the resultant energy, speed, or temperature of the outgoing neutron or triton. The tritons become embedded into the solid metallic shell surrounding the target chamber. The neutrons, however, are unabated by the chamber and during production are expelled equally in all directions or isotropically. The target chamber in this specific system was configured into a cylindrical shape. Taking that into consideration and knowing that a pressure gradient occurs across the gas target, the shape of the neutron production more closely resembles a tear drop than a sphere (fig. 6). The highest neutron production occurs at the first point the ion beam comes into contact with inside the target chamber. Neutron production tapers off as the ion beam loses energy from no longer being accelerated and by being slowed or attenuated within the gas inside the target chamber. The tail end of the tear drop is a result caused by the center of the ion beam having the most energy impinging into the target and, therefore, a higher penetration depth into the chamber itself. The ion beam also becomes less dense as it extends away from the center of the target chamber. This portion of the ions does not have the full acceleration or target penetration that the center portion does.

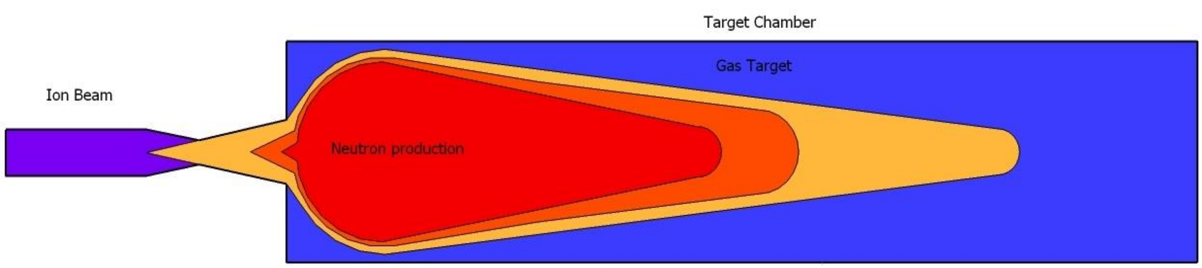


Figure 6
Depiction of the shape of the neutron output from the PNL generator

In all, this particular PNL prototype design has a maximum accelerating potential difference (voltage) of 300 kV. The maximum ion beam current that is achieved is 30 mA at 9 kW of power. With the beam optimized, the neutron yield that can be achieved is approximately 1E11 n/s. However, during the normal operating conditions in its initial configuration, the nominal yield was in the range between 2E10 to 4E10 n/s. This loss was attributed to several factors and will be mitigated and reported on in future reports. The lifetime of this system is not based off of target life since there is no concern for deterioration of a gas target that is constantly replenished. Sustained operations are completely dependent on maintaining all the surround components in this design, which is complementary to any current x-ray generator. Figure 7 shows an image of this long lifetime neutron generator.

Figure 7
PNL high yield, long lifetime neutron generator

Overview of the Starfire Industries Neutron Generator

The Starfire Industries neutron generator consists of their own original design on an ion source, which is also used to create a deuterium plasma. This system uses a deuterated solid target loosely based off of previous commercial neutron generator target designs, but it is more robust and maintains a consistent output at full power. The advantage of using a solid target is the ability to create a very dense ion beam over a short distance between the ion source and the target. This allows for the reduction in the space required between high voltage components as well as the overall size of the entire generator.

Initially, the Starfire prototype achieved a maximum yield of 3E9 n/s at 200 kV using only a bare copper target. The maximum ion beam current that was used is 37.5 mA at 7.5 kW of power. However, during continuous use, it was found that it nominally ran at yields in the range of 1.3 to 2E9 n/s. During the testing phase, upgrades to the target materials and cooling system allowed for yields to be consistently above 1E10 n/s. Due to the materials and design of the target, the expected lifetime is in excess of 10,000 hr. This is attributed to the ability to regenerate or repopulate deuterium as well as effective and efficient cooling across the target, unlike previous commercial generators. Figure 8 shows the completed Starfire Industries Pictoris Radiographic System (PRS) as installed at ARDEC. The generator is enclosed in a self-contained shell, which also includes all the vacuum, cooling, and electronics to control the system. This figure also shows the moderator and collimator setup, which will be discussed later in this report. Please note, the image does not show the high voltage power supply, which is a commercially available piece and is comparable to the size of any supply used for an x-ray generator.

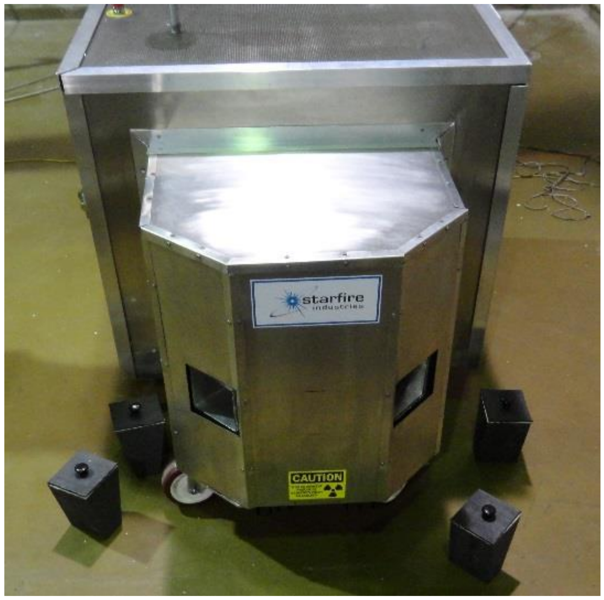


Figure 8
Starfire Industries PRS with its enclosed high yield, long lifetime neutron generator

IMAGING EXPERIMENTS ON THE PHOENIX NUCLEAR LABORATORIES GENERATOR

Initial Neutron Radiographic Setup

Moderator Designs

The moderator assembly for the PNL system was originally modeled using Monte Carlo N-particle (MCNP) simulation software. The modeling confirmed that acceptable dose rates would be achieved outside of the shooting cell and that neutron flux could be directed outward if a collimator was present. The modeling was more for safety than it was for function. However, most of the design in this section was empirical, since additional MCNP modeling was unavailable. The moderator itself mainly consisted of nuclear grade graphite in brick form. The bricks were stacked as close to the target chamber as possible, but some air gaps were present affecting the thermalization efficiency (fig. 9). For preliminary data, this was treated as negligible but will be an area of improvement later in the project. The minimum distance of graphite in any one direction was 30.5 cm but on average exceeded 61 cm. Several advantages of graphite as a moderator include minimal activation products created internally within the moderator and minimal length to fully thermalized 2.45 MeV neutrons. On the outside of the moderator assembly, several layers of high density polyethylene (HDPE), boric acid filled plates, Boroflex sheets, and lead sheeting and foils were used. Boroflex is a proprietary product of specialized flexible rubber sheets containing high amounts of boron-10. Most of this exterior material was put in place to reduce the dose rates seen on the outside of the shooting cell. The lead was used to reduce gamma and x-ray scatter produced from activation while the system was on. In addition, all these surrounding materials reduced scatter inside the room and became less of a contributor to reducing the image quality. It did not completely eliminate neutron and photon radiation scatter, but it made an impact on imaging.

(a)
Beam port side or front face

(b)
Rear face

Figure 9
Initial PNL moderator setup

An added component that can be seen in figure 9 is the supplemental high density concrete blocks. These blocks were added prior to the target chamber to eliminate neutron, gamma, and x-ray contamination that occurred. This was a result of extraneous gas exiting the ion beam input site due to a pressure drop that is inherent to the design. This escaping gas traveling back toward the ion beam allows some fusion events to take place prior to the actual target plane and was a source of radiation that was harmful to the initial image quality obtained. This small tail of escaping gas was depicted in figure 6.

Collimation Designs

The initial collimator configuration was identical to the originally designed Cf-252 unit used throughout the experiments performed in references 4 and 5. This collimator was a HDPE cylinder that contained bismuth rings, a lead liner, and a coating of gadolinium paint. Initially, the collimator was grossly fitted into place between the graphite bricks of the moderator. An approximate 5.08-cm gap of air was present between the target chamber and the aperture of the collimator. During this portion of the project, it was seen as negligible but is another area of improvement that will be reported on later. Future testing with the PNL system also plans to incorporate a second beam line on the opposite side of the moderator assembly. This second beam line is expected to use the lead lined HDPE cube that was used within the experiments provided in reference 5.

Imaging Setup Variations

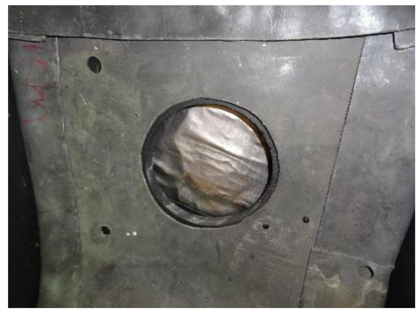
Radiation Scatter and Contamination Issues

During all the experimental tests within this paper, consistent changes were made to compensate for radiation scatter and in-line beam contamination. With any ion accelerating system, there will always be a source of Bremsstrahlung radiation in the form of x-rays. During the acceleration of positive ions, an opposing current of back streaming electrons occur. These electrons must be reduced or the opposing current will reduce the beam current entering the target region. A simplistic design would include a toroid shaped plate that surrounds the ion beam, which attracts the back streaming electrons out away from the beam. This component is commonly referred to as a suppressor. A consequence, though, is the electrons will be slowed and will create the release of x-rays in the process. This radiation will follow the same characteristics as in an x-ray generator. The spectrum and maximum photon energy is directly related to the materials within the target or electron suppressor and the maximum potential difference used to accelerate the ions. With

the PNL generator, the maximum voltage input to the accelerator is 300 kVp. Therefore, it can never create x-ray photons over 300 keV. These photons must be reduced as much as possible. Otherwise, they will cause blurring, mottling, and shadows at the image plane.

In the case of the PNL system, most of these x-rays are shielded by the large graphite moderator along with the use of lead and concrete on the exterior. However, the aperture opening through the collimator allows a direct path for this unwanted photon radiation to expose the image media. During the initial tests, lead sheets were laid over top of the collimator opening to reduce this contamination. Thicknesses varied from 0.01 cm (0.004 in.) up to 0.051 cm (0.02 in.). Figure 10 shows the beam line filter to reduce photon contamination at the image plane.

(a)
Open collimator



(b)
Foil covering

Figure 10
Beam line filter to reduce photon contamination at the image plane

In addition to the x-rays, the neutron activation products produced also degraded overall image quality for the same reasons. Activation occurs from the target chamber itself, in the surrounding laboratory equipment, the air, from the floor and side walls of the room, and even in the imaging cassette itself. The steps to reduce the surrounding contamination are generally the same—by using lead, concrete, and other gamma absorbers.

Neutron scatter is also a concern, which can cause image degradation too. In the production of fast energies, some neutrons will still escape the moderator under general circumstances. This is caused by incomplete coverage of absorbing materials surrounding the moderator and a result of the probability for complete capture of every neutron produced. There are also some scattered neutrons that will pass through the collimator and traverse through the image plane. Similar to dealing with the activation products, materials that are heavy neutron absorbers are placed around the image plane. Materials such as boron, gadolinium, and HDPE can be used, but additional constraints occur. These materials also create activation products when placed within a high neutron radiation field. This produces additional photon radiation that can reach the image plane. It took extensive empirical trials throughout this project to sufficiently layer neutron and photon absorbing materials so that minimal scatter radiation reached the image plane.

The easiest method to prevent exterior scatter from outside of the direct neutron beam is to construct a surrounding shell around the image plane. This shell is generally referred to as a beam port. Most beam port designs in use with an imaging reactor involve a concrete hallway that is completely enclosed and is a direct extension off of the core. At the end of the port is some type of doorway that can allow access to slide image media, film cassettes, parts, and other fixturing inside in line with the beam. In some cases, the beam port is lined with borated materials to reduce scatter directly next to and behind the image plane. The first iteration to mimic this beam port concept is provided in figure 11. It is a simple wood frame that was lined with lead on the inside while lined with

Boroflex on the exterior. The table supporting the beam port was also coated in lead sheets to further assist in reducing scatter coming from the floor. Although this was a crude design, it did eliminate a significant portion of scatter surrounding the image plane, which can be seen in figure 12. Figure 12a shows the system without any scatter guards, figure 12b shows it with a backstop and added concrete on the sides of the moderator, and figure 12c shows it using a beam port.

Figure 11
Photographs of the first beam port constructed to reduce outside neutron and photon scatter on the PNL system

(a)	(b)	(c)
No scatter guards	Backstop and added concrete	Beam port

Figure 12
An image comparison during the reduction of external scatter

Beam Port Experiments

As this project progressed, the reduction in scatter radiation became more and more important. Several revisions were made to the beam port to ensure as much contamination as possible could be removed from the image plane. The areas of deficiency in the initial beam port included: the use of wood in the construction, insufficient coverage of the borated flexible mats, inadequate coverage of the photon blocking lead plate, poor shielding and coverage behind the image plane, and overall ease of use to place fixturing and cassettes inside. These issues caused unwanted prompt gamma rays to be produced, allowed scattered thermal neutrons and exterior scattered photon radiation back into the image plane, and permitted unwanted backscattering to occur. Additional constraints in the design included the difficulty in placing IQIs, inspection pieces, and image media into the proper orientation prior to imaging.

In order to increase image quality, a significant redesign and change was necessary. The following modifications attempted to fix or reduce the impact of each issue mentioned. The framing was made of extruded aluminum, which is a very low scatter producer and absorber of thermal neutrons. Aluminum also has a low impact on any remaining fast neutrons present within the direct beam. The exterior was once again layered with borated flexible material that contained 25% content by weight. The gaps between the borated material were reduced as much as possible without adding excessive costs or complications. Most of the unavoidable gaps were left closer to the collimation end. The interior contained lead sheeting and also followed the same criteria as the borated sheet regarding material gaps. This design also was retrofitted with an easily accessible rear end that has an attached swinging door that allowed easy access to the interior. This door was also coated and layered in the same method as the main assembly of the beam port and reduced backscattered radiation. The interior was coated with gadolinium paint to capture any remaining thermal neutrons without producing any significant increase in other radiation byproducts that could impact the exposure at the image plane. The interior itself was also upgraded to include a linear bearing that slides down the center of the assembly to allow easy changes to the ratio of the beam length to aperture diameter (L/D) as needed. The results of this redesign will be covered in later publications, but the expectation is that there should be a high probability that it becomes an added benefit in comparison to what is shown within this report. Figure 13 shows the next redesigned and modified beam port.

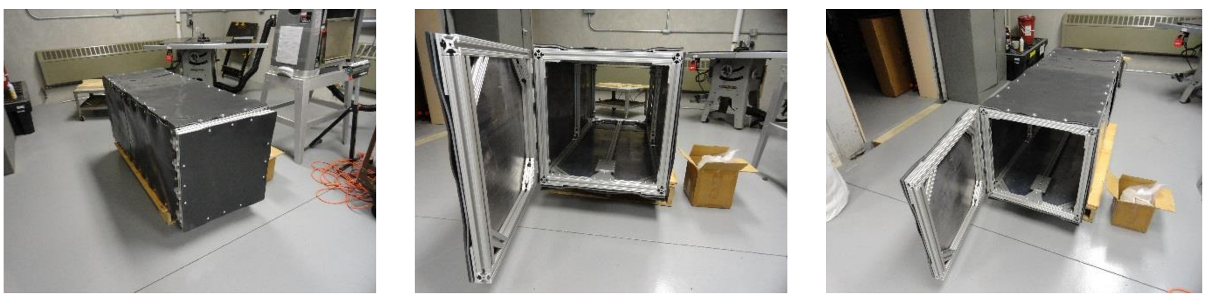


Figure 13
Photographs showing the next redesigned and modified beam port after its construction

IMAGING EXPERIMENTS ON THE STARFIRE SYSTEM

Starfire System Attributes

The Starfire system is unique in its design, not only from the standpoint of the generator itself, but also in its 5-collimator port moderator. Several of these collimator openings can be seen in figure 8. This attribute alone allows the system to image at multiple planes simultaneously and is a direct advantage for production use. This quality also allowed faster throughput when initial image experiments and quality assessments were being performed. This added feature was uniquely built with a proprietary design and was modeled to eliminate or heavily reduce extraneous scatter between each collimator opening. The moderator is mainly made of nuclear grade graphite to also reduce unwanted activation gamma radiation from occurring. The added capability of having multiple imaging planes can allow diverse inspection setups, production applications, research and development inspections, and other investigations to occur all at the same time. This added design is comparable to an x-ray system using a target that allows for a panoramic beam creating a 360-deg exposure area surrounding the target. Such setups usually have a ring or individual segmented stations built for increased quantity and throughput.

The overall size or footprint of the system in comparison to its maximum potential yield also makes it very potent and more applicable to spaces, exposure rooms, and other compact areas, which many inspection sites would have in place already within the DoD community. With planned future upgrades pushing the yields above 2E10 n/s, this system shows promise of expanding the NR method to users that could not otherwise obtain and use it practically. The user control station and graphic user interface and software have also been developed to be technician friendly and can be operated with minimal interaction from the user. The Starfire system is also built on castors and can be easily moved from one shooting cell to another or repositioned later if needed.

Radiation Scatter and Contamination Issues

As is the case with practically all radiation producing devices, scatter and contamination were two focus areas that had to be assessed with the configuration of the Starfire PRS prototype system. The initial setup of the system did not include any portion of the imaging plane that started as nothing more than elevated aluminum fixtures that were placed several inches off of the floor. This quickly showed there was a scatter issue coming from the floor in both forms of scattered neutrons and activation gammas. In figure 14, a secondary image on the first test shot clearly shows a radiation shadow coming up from in front of the image plane. To begin reducing this effect, crude beam ports were put into construction. These early ports were mainly diverging tunnels made of concrete to match the area of coverage of the direct neutron beam and encompass the entire 14 by 17-in. film. The first L/D ratios that were used varied between 16 and 20 with an aperture diameter of roughly 2 cm (0.79 in.). Figure 14a shows no scatter or port shielding, figure 14b shows the partial walls in place, and figure 14c shows the addition of a backstop and ceiling.

(a) (b) (c)

Figure 14
Photographs showing the construction of the beam ports

With this preliminary design, the initial imaging trials that occurred while the beam ports were in the process of being made also showed that additional side scatter radiation was affecting the image quality. As the concrete was added to create the side walls, the amount of scatter was reduced but not eliminated. The beam ports were beginning to show the elimination of the cross talk between the separate collimation openings. Due to both the neutron and photon radiation scatter and contamination that was reaching the image planes, additional materials were added. This was to ensure as much of both types of radiation scatter and contamination could be removed. These materials included coating the interior of the port floors and walls with thick layers of gadolinium infused paints, adding lead sheets to the floor of the beam ports, and adding lead bricks under and directly aside of the image plane region. Figure 15 shows the early evolution of going from no scatter guards or beam ports to partially constructed walls as well as the addition of lead back stops and temporary gadolinium painted HDPE to reduce any unwanted radiation entering the beam path from above. Figure 15a shows no scatter or port shield, figure 15b shows partial port walls in place, and figure 15c shows the first full beam port design.

(a) (b) (c)

Figure 15
An image comparison of the early evolution of the beam ports

Progression in Beam Port Design

As the preliminary testing of the Starfire PRS neutron generator occurred and after the first revision of the beam ports was built, further adjustments were made to increase image quality. In between different imaging trials, the clarity, sharpness, definition, and range in latitude were assessed to determine if and where remaining scatter and/or contamination were present. The overall results of these early experiments showed that added back scatter and "sky shine" were degrading the achievable image quality from behind and above the image plane, respectively. To counteract these two areas, thick lead sheeting and plates ranging between 0.64 and 1.27 cm were mounted on various frames to hold them in place directly behind the image plane. Additional lead was added to cover the top end over the concrete beam port walls. Additional gadolinium coated HDPE and/or Boroflex were used over top of the lead on the ceiling portion of the beam ports. This was meant to absorb any extraneous thermal neutrons that may have been scattered within the exposure room above the system. The purpose for the specific layout of the layers was to first remove unwanted neutrons from entering outside of the beam ports. In the interaction with borated materials, some prompt activation gammas can occur in the 480-keV range, while in the HDPE, some 2.2-MeV gamma rays can result from the hydrogen (ref. 6). The underlying layers of lead were meant to remove this added radiation created by the neutron interactions and also to block any gamma photons that were created outside of the beam ports elsewhere. Figure 16 shows the complete 5-beam port assembly (fig. 16a) and part fixture placed inside at the image plane (fig. 16b).

(a) (b)

Figure 16
The completed assembly and the general placement of the part fixture inside one of the ports

Future testing with this design is expected to occur because this first draft design was not ideal for optimized radiographic imaging. The area of coverage is not completely enclosed from the outside, and some gaps between the materials are present that allow some scatter to enter in. The next revision is planned to be a more sophisticated setup with potentially a framework of lightweight extruded aluminum to allow for sliding movement of the beam stops and translating movement of the fixtures for easier adjustments to the L/D ratio. With a frame of this type, the lead boron lining materials could be more easily mounted in full sheets so the actual enclosure excluding the beam stop would be one solid structure with no openings to the exterior of the shooting cell. This is most likely the path toward a production ready design that would both increase image quality and decrease labor time to prepare, align, setup, and use during repetitive image acquisition. Further changes and developments on the beam port design for use with the Starfire PRS neutron generator will be discussed in later reports.

RESULTS AND DISCUSSION

Neutron Exposures Acquired Using the Phoenix Nuclear Laboratories System

Image Quality Achievements

The initial quality that was achieved at the beginning of this project was poor in comparison to the needs, expectations, and requirements for production use. However, the data did show the potential that the PNL system can be a practical means for neutron imaging of DoD components. Several factors played into the events accomplished that are described within this report. This included the scale down of the maximum output used during this testing phase of the generator that was held at 260 kV instead of the systems designed 300 kV. Future tests are expected to be done at the 300-kV output, which will increase the neutron yield and decrease exposures significantly from the images presented in these works. The moderator assembly was constructed nonuniformly, and a higher thermalizing efficiency is possible resulting in a higher flux at the image plane if corrected. An additional constraint that should be considered when reviewing the results of these experiments is the first revision of the beam port. It was constructed with piece meal hardware and had various imperfections that impacted the overall achievable image quality.

Even with the above mentioned deficiencies of these experiments, proof of principle was obtained. The following examples in figure 17 show the preliminary ability of this system and setup. The layout is presented such that the images are shown with their photograph and neutron radiograph from left to right, respectively. All of the images are preceded by the technique and the measured image quality as per ASTM E 545 (ref. 2). The quantitative measurements from this standard include: the effective thermal neutron content of the beam (NC), the scattered neutron content (S), the gamma content (γ), the pair production content (P), and the image optical density readings [Hurter and Driffield (H and D)]. The qualitative measurements include the image sensitivity (H and G) and the overall assessed image category rating (Cat.). For each one of these characteristics, a separate category rating was placed in parentheses for comparative purposes. Also provided with each image comparison are the physical traits defining the setup of the exposure. This includes: the conversion screen type, the thickness of the beam filter used, the length of the image plane to the aperture (L), the geometric ratio of the setup (L/D) where D was a constant at 5.08 cm (2 in.), the geometric unsharpness (Ug), the total exposure time (t), the type of film or image media used, and any other additional comments or notes on the setup used to acquire the images shown.

NC	**S**	**γ**	**P**	**H and D**	**H**	**G**	**Cat.**
23.58 (<5)	**0.81 (1)**	**3.25 (2)**	**2.44 (1)**	**1.29**	**NA**	**5 (3)**	**NA**
Converter	**Beam filter thickness (in.)**	**L (in.)**	**L/D**	**Ug (in.)**	**t (hr)**	**Image media**	**Comments**
Gadolinium 15-μm thick backscreen Lead: 0.01 in. front and back	**0.008**	**60**	**30**	**0.033**	**47.5**	**Kodak AA400**	**Under exposed**

(a)
Shot 12

Figure 17
Image comparison of test shots 12 and 13 with the PNL system

NC	S	γ	P	H and D	H	G	Cat.
22.92 (<5)	4.17 (1)	0 (1)	0 (1)	0.49	NA	3 (5)	NA
Converter	**Beam filter thickness (in.)**	**L (in.)**	**L/D**	**Ug (in.)**	**t (hr)**	**Image media**	**Comments**
Gadolinium 15-µm thick backscreen Lead: 0.01 in. front and back	0.016	70	35	0.029	60	AGFA D4sc	Under exposed

(b)
Shot 13

Figure 17
(continued)

A major point to note is that these exposures were below the optical densities allowed within ASTM E 545. The recommended range is between 2.0 and 3.0; however, in many cases, adequate neutron radiographs can be accomplished within the 1.5 to 2.0 range. Since these exposures were low, the NC and H values were well below acceptable. This is the reason why no film category could be provided. In light of this, a significant amount of data was obtained on photon content, neutron to gamma ratios, general spatial resolution, and several of the specific characteristics to penetration for various parts and materials. Future testing and results are expected to be at full exposure, showing a much greater potential for quality neutron radiographs that are category 4 or better.

Scintillator Trials

Throughout the preliminary testing stage of the PNL system, several off-the-shelf neutron sensitive scintillators were examined. Although the gadolinium screen in hand provided excellent clarity, sharpness, latitude, and had no susceptibility to x-ray or gamma radiation, it had the deficiency of being a slow converter.

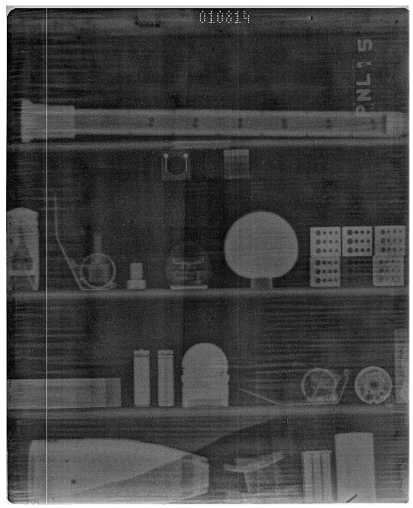
The second type of scintillator that was examined was the Li6F:ZnS compound manufactured by Eljen Technologies, Sweetwater, TX. The samples under testing included the HD and non-HD versions with emulsion thicknesses of 0.5 and 0.32 mm. These series of screens were mounted to an aluminum backer for support. The overall assessment of these screens shows that exposures can be reduced by approximately 60% in comparison to the previous Gd conversion screens. The neutron conversion efficiency of this series and compound was also very high with a minimal photon reaction, while the difference from the thicker screen showed a small decrease in exposure time by roughly 4.2% in comparison to the thinner 0.32-mm version. The apparent clarity and resolution was slightly affected but was dismissed for initial testing. An issue of consistent density across the entire image plane was visible though. The method in which the emulsion was printed, pressed, or layered created markings, dimples, and other scratch-like shapes into the emulsion. This, in turn, created a different surface area and amount of conversion material exposing the film resulting in excessive artifacts in the image itself. Considering this was the first attempt using this material for this application, the images were satisfactory. For the sake of throughput, most of the images shown are underexposed but still reliably show the variance from each setup and trial. Figure 18 provides several examples and test exposures taken with the PNL unit and the variations of different scintillator screens used.

NC	S	γ	P	H and D	H	G	Cat.
16.83 (<5)	0.99 (1)	0 (1)	1.98(1)	1.03	NA	5 (3)	NA
Converter	Beam filter thickness (in.)	L (in.)	L/D	Ug (in.)	t (hr)	Image media	System – Power
Eljen EJ-426HD (SN04-01) Li6F:ZnS_backscreen 0.5-mm thick Lead: 0.01 in. front and back	0.02	70	35	0.029	20	Kodak AA400	PNL – 260kV* 20mA = 5.2kW

(a)
Test shot 14

Figure 18
Image comparisons of test shots 14, 15, and 16

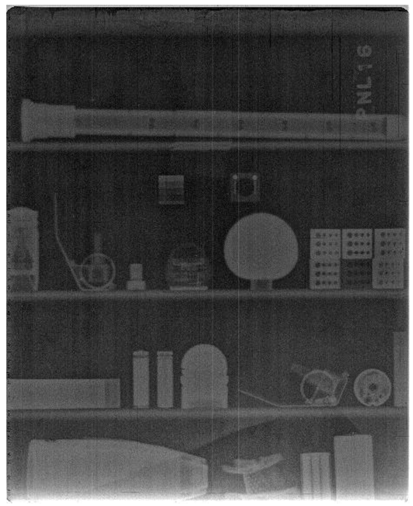
NC	S	γ	P	H and D	H	G	Cat.
20.21 (<5)	4.26 (1)	-5.32 (1)	2.13 (1)	1.03	NA	5 (3)	NA
Converter	**Beam filter thickness (in.)**	**L (in.)**	**L/D**	**Ug (in.)**	**t (hr)**	**Image media**	**System – Power**
Eljen EJ-426HD (SN03-01) Li6F:ZnS_backscreen 0.32-in. thick Lead: 0.01 in. front and back	0.02	70	35	0.029	20	Kodak AA400	PNL – 260kV* 20mA = 5.2kW



(b)
Test shot 15

Figure 18
(continued)

NC	S	γ	P	H and D	H	G	Cat.
12.77 (<5)	2.13 (1)	2.13 (1)	4.26 (3)	0.49	NA	3 (5)	NA
Converter	Beam filter thickness (in.)	L (in.)	L/D	Ug (in.)	t (hr)	Image media	System – Power
Eljen EJ-426 (SN02-01) Li6F:ZnS_backscreen 0.50-in. thick Lead: 0.01 in. front and back	0.02	70	35	0.029	6.5	Kodak AA400	PNL – 260kV* 20mA = 5.2kW



(c)
Test shot 16

Figure 18
(continued)

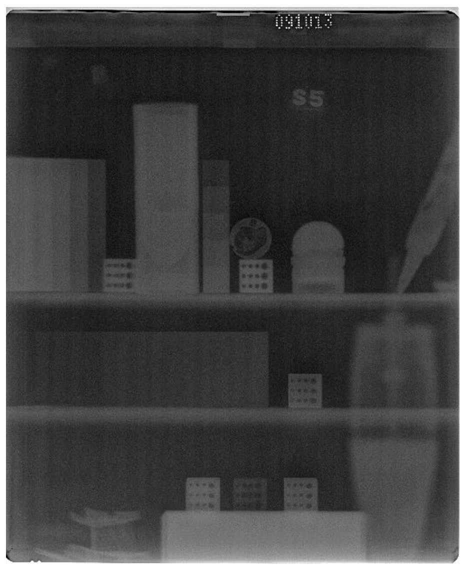
Neutron Exposures Acquired Using the Starfire System

Image Quality Achievements

Initially, there were similar results in overall image quality, excluding the change in geometric unsharpness from use of a smaller L/D than with the PNL system. The contrast of the images was slightly lower too. The contrast differences, however, can partially be accounted for since different combinations of conversion screens, film types, and other filters are not identical from the previous images. In the exposures shown in figure 19, a beam purity indicator (BPI) and sensitivity indicator (SI) were not available to quantify the results, but the ARDEC IQI set was used and shows attenuation values consistent with a neutron radiograph. The images in figure 19 also show that the exposure or test shot number is very attenuating since they are coated with gadolinium infused paint, whereas the lead letter "P" in the upper left hand corners is very faint. This does, however, show that some photon radiation is present and contaminating the exposure slightly. This was to be expected since very little beam line filtration was used in the images shown in figure 19. With the multiple beam port designs, the exposure difference from one beam line to another was minimal when considering the length of these exposures to begin with. No other significant

differences were seen between comparative images of the different beam ports, which is a positive takeaway from these initial tests.

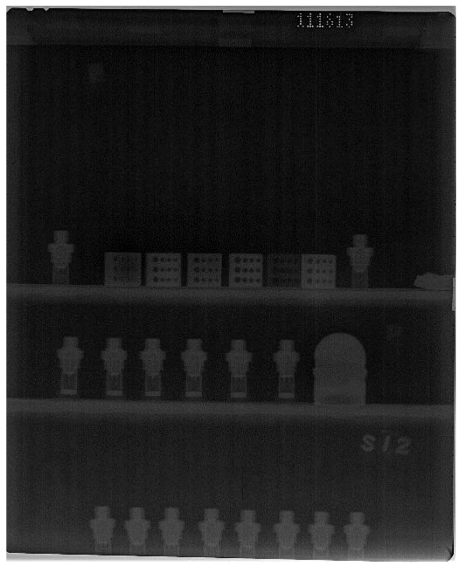
NC	S	Γ	P	H and D	H	G	Cat.
NA	NA	NA	NA	1.50	NA	NA	NA
Converter	Beam filter thickness (in.)	L (in.)	L/D	Ug (in.)	t (hr)	Image media	System – Power
Gadolinium backscreen 15-µm thick Lead: 0.03 in. front and 0.01 in. back	0	40	17.5	0.057	20.5	Kodak AA400	200V 25mA = 5kW



(a)
Test shot S5

Figure 19
Image comparisons of test shots S5 and S12

NC	S	Γ	P	H and D	H	G	Cat.
NA	NA	NA	NA	0.84	NA	NA	NA
Converter	Beam filter thickness (in.)	L (in.)	L/D	Ug (in.)	t (hr)	Image media	System – Power
Gadolinium backscreen 15-µm thick Lead: 0.01 in. front and back	0.009	40	17.5	0.057	50.75	AGFA D3sc	180V 20mA = 3.6kW



(b)
Test shot S12

Figure 19
(continued)

Scintillator Trials

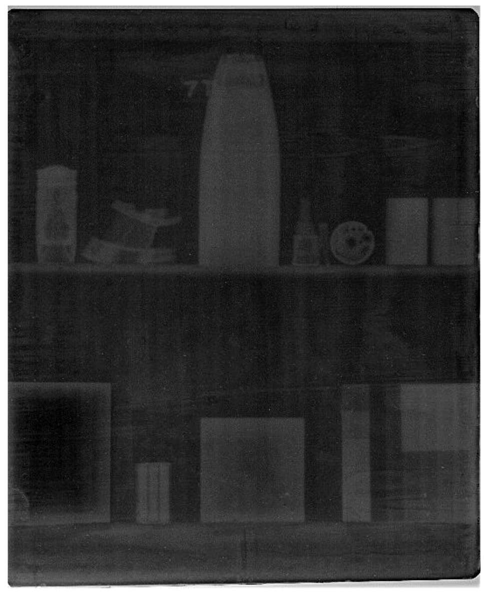
Additional tests were performed using different scintillating conversion screens on the Starfire system. Various combinations of front and back screen setups were attempted. Some of the exposures that are shown in figure 20 used phosphor screens that were made with a different method of applying the emulsion to the backer plate. These screens were developed in an effort to reduce the artifacts that were shown in previous examples. Overall, it was very evident that trying dual screen combinations created too much distortion and poor spatial resolution, even though exposure speeds were drastically faster. Further investigation into using a dual screen combination with film may be presented in future works. However, to develop a neutron specific digital detection media only, the results from single conversion screens are applicable. A digital detector primarily only has contact with a single conversion screen and is why only single screen data is relevant.

NC	S	γ	P	H and D	H	G	Cat.
4.44 (<5)	0.37 (1)	-1.48 (1)	1.85 (1)	2.70	NA	2 (<5)	NA
Converter	Beam filter thickness (in.)	L (in.)	L/D	Ug (in.)	t (hr)	Image media	System – Power
Eljen EJ-426-0-PA, 0.32-mm Li6F:ZnS_Front; Eljen EJ-426-0-PA, 0.50-mm Li6F:ZnS_back Lead: 0.03 in. front and 0.01 in. back	0.02	35	17.5	0.057	18.5	Kodak AA400	160V 24mA = 3.84kW

(a)
Test shot 1S

Figure 20
Image comparisons of test shots 1S and 7T

NC	S	γ	P	H and D	H	G	Cat.
7.29 (<5)	0.37 (1)	1.62 (1)	7.29 (5)	1.28	NA	2 (<5)	NA
Converter	**Beam filter thickness (in.)**	**L (in.)**	**L/D**	**Ug (in.)**	**t (hr)**	**Image Media**	**System – Power**
Eljen EJ-426HD2-PA, 0.50-mm Li6F:ZnS_back Lead: 0.03 in. front and 0.01 in. back	**0.02**	**35**	**17.5**	**0.057**	**16.25**	**Kodak AA400**	**165V 34mA = 5.61kW**

(b)
Test shot 7T

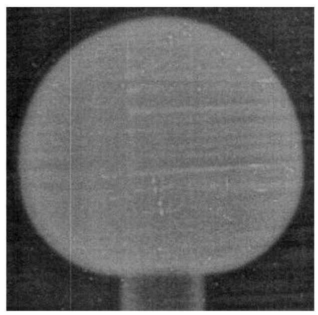
Figure 20
(continued)

The examples provided in figure 20 show similar results with unevenly coated phosphor screens but also exhibit a substantial reduction in contrast. The values taken from the BPI showed that the images acquired had a lower neutron content, but this is a result of a lower thermal content. The images still clearly show a neutron radiograph. However, the spectrum of the neutrons creating the radiograph has a wider range of energies including a large portion of epithermal content. In this report, the process of performing a series of activation foils with and without cadmium covers is not shown. However, from the BPI values and the reduced contrast seen throughout the tests in figure 20, it is evident that the cadmium ratio is lower than what is expected. Further tests in increasing moderator efficiency and more specifically trying better in-line beam filtration is needed and will be presented in later reports. Overall, it has been shown that this system can potentially create useable neutron radiographs with an effective exposure time in less than 6 hr. This includes the use of multiple beam lines simultaneously. For the images shown in figure 20 that do not contain the BPI and SI, a representative sample was used for the data.

CONCLUSIONS

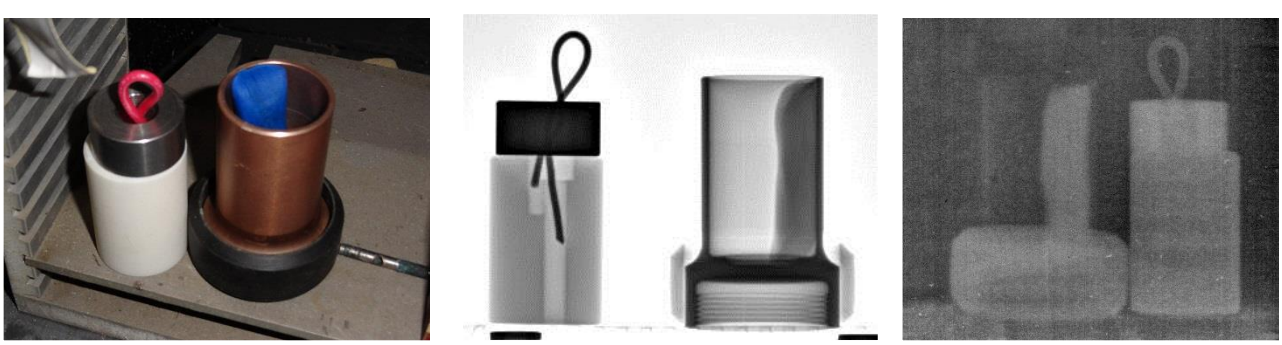
Item Comparison of Neutron and X-ray Images

Although not fully described in this report, several components that were imaged during this initial stage showed materials and conditions that could not be seen previously using conventional x-ray imaging. Some of the components that were imaged using neutrons demonstrated the ability to penetrate through highly complex and layered designs and enhance the detection of the internal sub-components or materials. When x-rays were used in the same examples, the photon radiation either over penetrated (meaning it removed the contrast needed to interpret the design) or had too much internal scatter within the part to maintain a useable exposure. The following figure represents a neutron image showing only the internal energetic fill inside a grenade, while the casing and liner are practically invisible. For the same item, an x-ray image would be comparable to the liners shown in figure 2, and the fill would be very hard to detect reliably.



A radiograph (neutron) of a grenade showing the explosive fill that is encased and surrounded by an unseen etched fragmenting liner

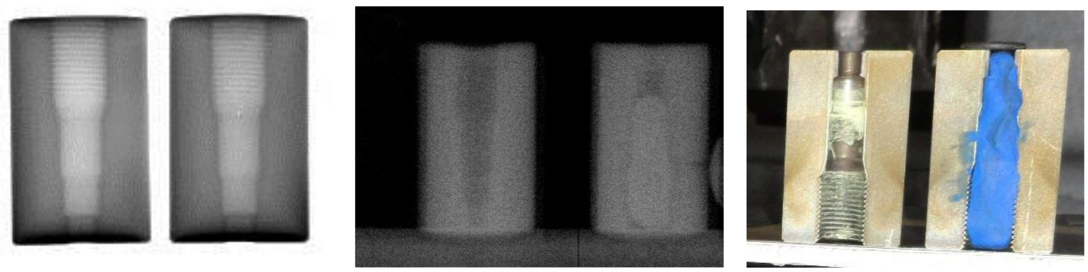
The following figures represent a sample made of a copper tube surrounded by a large rubber seal on the bottom and is partially filled with a clay type replica of energetic material (a). They also illustrate a sample made of a polyethylene tube and stainless steel torrid with an insulated copper wire placed inside. The x-ray radiograph (b) clearly shows the fine details of the parts, but even with heavy post processing, the large rubber seal is undetectable inside of the copper tubing. Unlike the comparative neutron radiograph (c), the neutrons are more attenuated by the rubber than the copper. The x-ray image also shows the wound copper wire inside, whereas the neutron image shows the exterior insulating layer.



(a) (b) (c)

A homemade setup of several materials

The following figures show a clear example of a situation where the x-ray image (a) makes it nearly impossible to detect the internal materials. The x-ray image shows that the clay is a small portion of the total attenuation and is not visible (a). The neutron image (b) in this figure can easily and clearly depict the internal materials. The clay simulant (c) used in the sample is a very small portion of the total attenuation of the entire part for the photon radiation. The same material has a much higher total attenuation for thermal neutrons. In this example, the fine detail of the part is not the important portion of the inspection, but rather the clear detection or presence of the internal material.



(a) (b) (c)

A homemade setup of a clay filled steel assembly

Future Developments in Generator Technology

In addition to the testing and development of the Phoenix Nuclear Laboratories (PNL), Morona, Wisconsin, and Starfire Industries systems, a parallel effort was underway in building the next generation designs for both technologies. More specifically, PNL is in the initial stage of upgrading the current P1 system to increase total power and efficiency of the ion beam to achieve the designed maximum yield of the system. At the same time of this effort, a completely new redesigned neutron generator is being constructed. The next system is expected to achieve yields exceeding 5E11 n/s (Deuterium – Deuterium). This new system is expected to contain a fully integrated heavy water moderator that will also help to increase the thermal content of the imaging beam. This next system is scheduled for a delivery in early 2016, after which time testing and verification will occur. The end goal of this next design is to be installed within a U. S. Army or Department of Defense (DoD) production facility for direct use in quality control of munitions and weapons system by means of neutron radiographic inspection.

Continuing Progress in Neutron Imaging

In short, this report details the early preliminary imaging for the PNL P1 and Starfire Industries Pictoris Radiographic System neutron generator systems for use in radiography. Most of these early images were underexposed, but a large amount of information was ascertained in order to move forward toward better image quality that is sufficient for DoD requirements. A few of the areas that were revealed included: knowing where scattered radiation was occurring within the shooting cells, the overall beam quality being produced, and general imaging characteristics specific to each system. This early analysis of these two systems and capabilities showed promise that respectable neutron radiographs can be acquired. This testing stage showed some deficiencies with the piece meal setup of the moderator and collimator assembly as well as the handcrafted beam ports. However, all of those areas, when addressed, are expected to increase the neutron flux at the image plane and decrease the loss during thermalization. The current yield of both systems is also lower than designed for because some debugging and verification had to be performed prior to using the systems at their full power ratings. The next report of this inspection capability is scheduled to

show what can be achieved when running at maximum capacity and with soundly constructed image components.

The next phase in this program is also going to continue further investigation into higher efficiency phosphors and scintillators to increase exposure and reduce acquisition time. Some of the materials under investigation are expected to add a further reduction of exposure and expose nearly twice as fast as the gadolinium conversion screens. The hope is to sustain or have a minute loss in overall resolution as well. If this portion of development can be accomplished, a fully functioning digital detector array specific for neutron radiography can be developed and integrated into these two systems. If accomplished, the images potentially could be compressed down into the sub-hour range. Additionally, using multiple ports may even further decrease the effective exposure time per image or part and make it fully feasible for full production throughput.

REFERENCES

1. Jurczyk, B., “High-Efficiency Long-Lifetime Neutron Generator for Radiographic Munitions and IED Inspection,” U.S. Army ARDEC SBIR Commercial Pilot Program contract no. W15QKN-08-C-0516, Starfire Industries, LLC, Champaign, IL, 2013.

2. Bailey, S. J., et al., “Annual Book of ASTM Standards,” volume 03.03, Nondestructive Testing, American Society for Testing and Materials, West Conshohocken, PA, 2011.

3. Radel, R., “High Flux Thermal Neutron Source,” U.S. Army ARDEC SBIR Phase II Enhancement contract no. W15QKN-08-C-0515, Phoenix Nuclear Labs, LLC, Madison, WI, 2013.

4. Zuber, S., “Applying Practical Neutron Radiographic Inspection to the Department of Army,” Technical Report AREIS-TR-16005, U.S. Army ARDEC, In press.

5. Zuber, S., “Optimization of the Army’s Fast Neutron Moderator for Radiography,” Technical Report AREIS-TR-17001, U.S. Army ARDEC, Picatinny Arsenal, NJ, In press.

6. Lindstrom, R. M., “Prompt-Gamma Activation Analysis,” volume 98 number 1, Journal of Research of the National Institute of Standards and Technology, National Institute of Standards and Technology, Gaithersburg, MD, 1993.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

A	Ampere
ARDEC	U.S. Army Armament Research, Development and Engineering Center
ASTM	American Society of Testing and Materials
BPI	Beam purity indicator
c	centi-, 1E-2
CT	Computed tomography
Cf-252	Californium isotope 252
D	Diameter of the collimator aperature
DoD	Department of Defense
eV	electron-Volt
G, H	Gaps and holes visible on the sensitivity indicator
H and D	Hurter and Driffield
HDPE	High density polyethylene
IQI	Image quality indicator
k	kilo-, 1E3
L	Length between the collimator aperture and the image plane
M	Mega-, 1E6
MCNP	Monte Carlo N-Particle software
n	neutron
NC	Neutron content, thermal
NDT	Nondestructive testing
NR	Neutron radiography
P	Pair production content
PNL	Phoenix Nuclear Laboratories, LLC
PRS	Pictoris Radiographic System - Starfire Industries, LLC
RT	Radiographic testing
S	Scattered neutron content
SI	Sensitivity indicator
t	time
u	micro-, 1E-6
Ug	Geometric unsharpness
UT	Ultrasonic testing
V	Volt
γ	gamma

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